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TITLE NEW SYSTEM FOR WIGGLER FABRICATION AND TESTING

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NEW SYSTEM FOR WIGGLER FABRICATION AND TESTING*

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ABSTRACT

A system approach is taken for the fabrication and testing of wigglers for free-electron lasers. Emphasis is placed on convenient, practical, assembly procedures that produce wigglers with high fields, two-plane focusing, and facilities for in-place adjustments. Equal emphasis is placed on rapid and precise techniques for measuring field errors, both before final assembly and afterward, during wiggler operation.

I. Introduction

The gain and efficiency of a free-electron laser (FEL) are determined by the interaction of a light beam and an electron beam in the wiggler. The performance will be degraded if either the light beam, the electron beam, or the wiggler is less than perfect. Normally the best that can be expected of the light beam is that it be in the lowest order Gaussian mode with the optimum Rayleigh distance. If the wiggler's gain is large, the mode may be distorted so as to either impair or benefit the gain. The electron beam must have a sufficiently small spread in longitudinal and transverse velocities. If the transverse velocities are excessive, the electron beam will wander away from the optical beam, reducing their mutual overlap, and thus the gain. If the longitudinal velocities have too large a spread, some of the electrons will not satisfy the resonance condition of the wiggler.

The wiggler problems[1,2] are similar to those presented above for the electron beam. The wiggler must be straight, and its magnets must give the electron beam the correct deflections down its length. If the deflections provided by the magnets are improper, the electron beam may wander out of overlap with the light beam. The beam may be deflected through an angle large enough that the remaining longitudinal velocity no longer satisfies the resonance condition. If the magnets are all too strong or too weak over a part of the wiggler, the amplitude of the oscillations of the electrons will be improper, producing an undesired change in the longitudinal velocity so that the resonance condition is not satisfied. If the wiggler is not straight, the electrons will find an improper field. This field can then cause any of the problems mentioned above.

The job of the wiggler's builder is to avoid the problems mentioned above. Normally he accomplishes this by following these steps:

1. Measure the properties of each magnet.
2. Assemble the magnets in the wiggler to compensate for the observed variations in the magnets, e.g., by arranging magnets in pairs so that an unusually strong one is followed by an unusually weak one.
3. Measure the fields of the assembled wiggler.
4. Modify the magnet arrangement to reduce the errors, e.g., by replacing "bad" magnets.

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5. Move the tested wiggler into its final setting.

6. Use diagnostic devices such as fluorescent screens to view the electron beam at several stations down the wiggler.

These on-line measurements assist in launching the electron beam correctly into the wiggler, guide in using the intermediate steering to compensate for remaining wiggler errors, and can be used to recognize changes in the wiggler's field that may occur with time.

Difficulties are usually encountered using these techniques. In our view, they result from six basic problems:

1. Field errors must often be limited to a few tenths of a percent or less, out the variations of the magnets currently available are usually several percent.[3,4]

2. Magnets should be characterized in terms of integrals of their fields measured along the trajectory followed by the electrons. Performing the required measurements is time consuming. The integral is usually approximated by a single field measurement taken at the point of closest approach of magnet and electron beam.

3. Some method is needed to adjust the field strength at closely spaced positions down the wiggler. The two techniques commonly employed, replacement of bad magnets and the use of external steering coils at a few locations, are too crude for use with high-performance wigglers.

4. After a wiggler is tested, it is moved to a new location and various equipment is added to it, e.g., a vacuum pipe through its center, diagnostic devices and steering stations along its sides, and pumps and thermal controls all around it. All of these devices have magnetic fields associated with them or are paramagnetic to some degree. These interfering effects are reduced as much as possible, but there is no good way to determine their magnitude inside the wiggler once it is on-line.

5. Fields change with time because of temperature,[4] radiation,[5] etc. No good way is available to measure these effects.

6. The wiggler is normally segmented to provide periodic diagnostic and steering stations. These stations sometimes present major disruptions[6] to the regularity of the wiggler and the vacuum pipe penetrating it. These disruptions can seriously affect the electron beam. One of the effects of major concern is wake fields.[7]

It is the purpose of this paper to present a new system for wiggler design, fabrication, and use that avoids most of the problems mentioned above. This system is based upon a new technique for measuring fields. The arrangement of this paper is as follows: In Sec. II we briefly present the elements of our system; in Sec. III we discuss the principles of the new measuring technique; in Secs. IV, V, and VI we present examples of the use of this technique with single magnets, with combinations of magnets, and with complete wigglers; in Sec. VII we discuss this technique used on-line with completed wigglers, in Sec. VIII we briefly discuss some of the problems we have encountered and their resolution; and in Sec. IX we present our conclusions.

II. FABRICATION AND TESTING SYSTEM

The system was designed to reduce the problems described above. The constraints that resulted are as follows:

1. A modified Halbach arrangement[8] of the magnets will be used.

2. Magnets will be stacked, i.e., grouped in a particular way, to reduce the variations found in individual magnets and to increase their overall strength.

3. A new technique will be used to adjust the field strength of stacked-magnet combinations so that they have integrated fields that are nearly identical to each other.

4. Additional steering will be accomplished with external coils that can be spaced very closely and may be computer driven.

5. No iron will be used, thus preventing problems with siting the steering coils.

6. Two-plane focusing will be accomplished with a novel arrangement of magnets.

7. The wiggler must be designed without penetrations (i.e., breaks) in the pipe passing through it. This precaution will reduce wake fields, but at the same time will eliminate the usual diagnostic stations.

8. An on-line field measurement system will be provided to verify that the field is always correct and to assist in achieving that state by adjustments of the steering coils.

Figure 1 shows a diagram illustrating the stacking concept. Stacking magnets in this way generates fields that are about 25% larger that those produced by a single layer of magnets. An algorithm can easily be developed for pairing magnets so that essentially all of the magnets can be used, with few rejects, and the combined field of each stacked pair will be very close to the average field. Additional selection criteria can be imposed, for example, to achieve approximate cancellation of transverse (parallel to the magnets) fields.

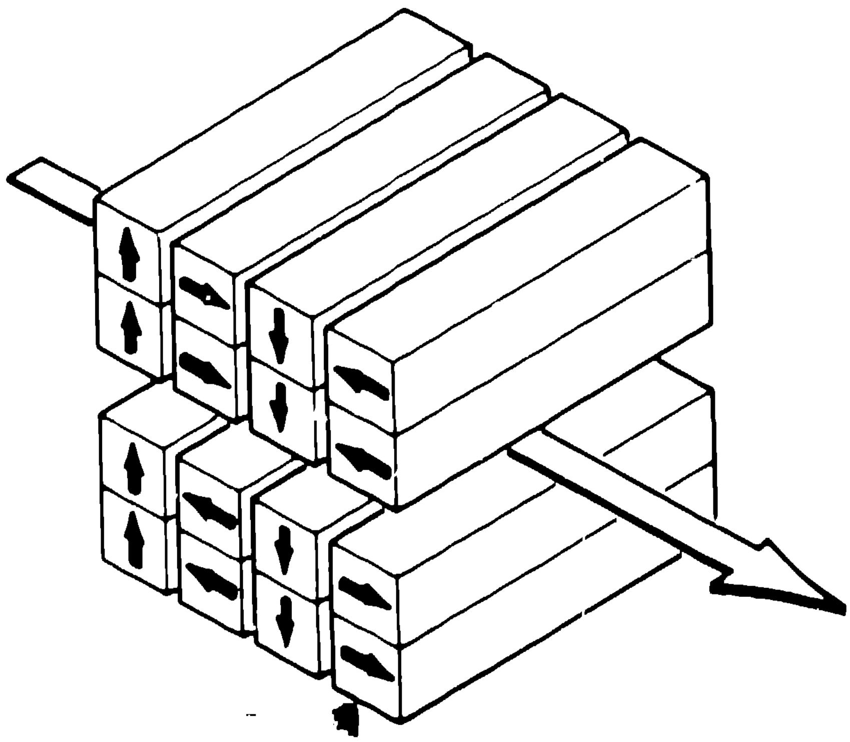

Fig. 1. Technique of stacking magnets to improve uniformity and increase strength.

Figure 2 shows the arrangement of magnets used to produce two-plane focusing. Calculations have been performed that show that this configuration produces approximately equal focusing in both transverse directions. Figure 3 shows plots of these results. Figure 3a is for the usual arrangement, lacking two-plane focusing, and Fig. 3b shows the results for the new magnet arrangement. Stronger focusing in the horizontal direction can be achieved by moving the added "focusing" magnets closer together or by adding similar magnets to the normal magnet pairs magnetized in the longitudinal direction.

Final adjustment of field strength is accomplished with the focusing magnets. These magnets add about 20% to the total field strength of a Halbach configuration. If their positions are adjusted inward, by 1% for example, the total field strength

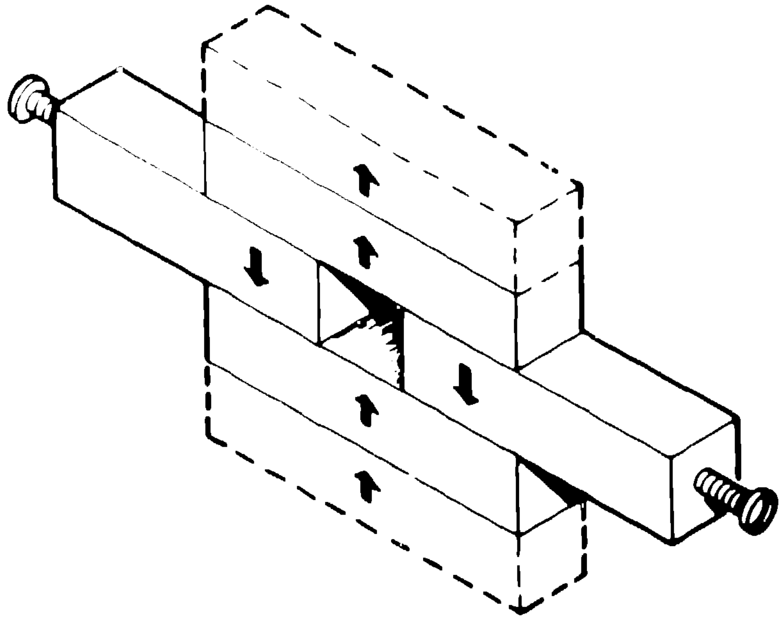

Fig. 2. Extra magnets introduced from the sides to provide two-plane focusing, increase field strength, and allow convenient adjustment.

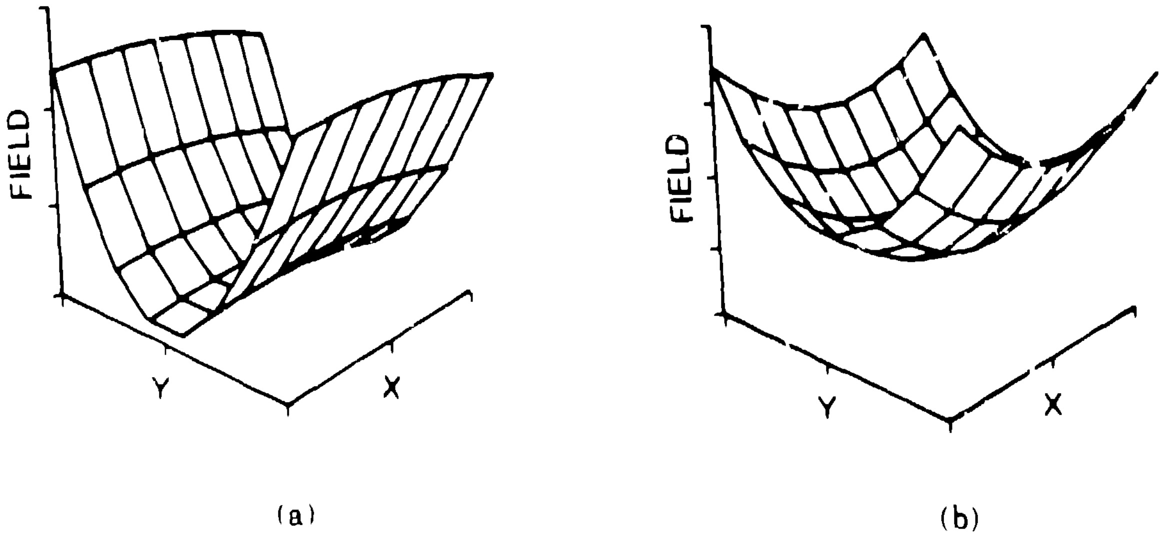

Fig. 3. Plots of field strength in both transverse directions: (a) without extra side magnets, (b) with extra magnets.

increases by about 0.2%. In this way, minor corrections can be easily made with insignificant changes to focusing.

We propose to arrange stacked magnets into one-half wavelength units, as shown in Fig. 4, composed of eight normal and two focusing magnets. Each of these half-wavelength frames will be adjusted to have nearly identical field integrals.

The frames include three mounting pins to allow them to be mounted easily in a kinematically stable manner on a rigid, massive base. This approach to wiggler design depends critically upon the ease and precision of the field-measurement technique employed, which we discuss below.

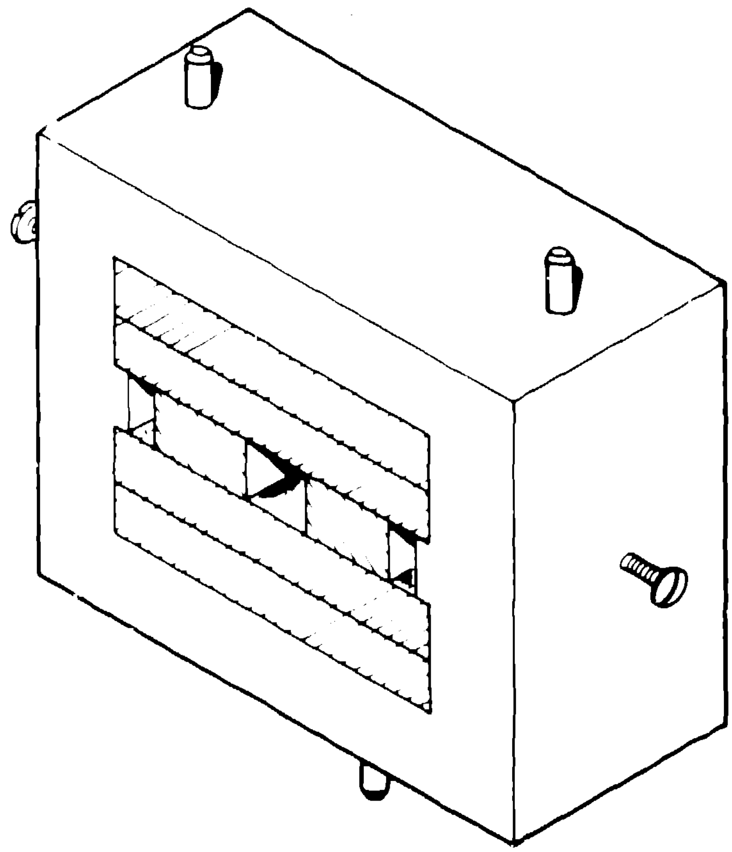

Fig. 4. Frame containing 10 magnets.

III. ELEMENTS OF THE FIELD-MEASURING TECHNIQUE

A thin wire, a pulsed current source, and a device to monitor the wire's position are used. The technique is an extension of the "floating-wire" method previously used[9] with wigglers, and used much earlier in various magnet and accelerator applications.[10] Figure 5 shows how these parts are arranged. A magnet is placed near the wire so that the wire's position is a replica of the path followed by an electron. When a short current pulse is passed through the wire, an impulse in the form of transverse momentum is transferred to the wire along its length. At every point, the momentum is proportional to the magnitude of the transverse field. The distributed momentum splits into two equal waves that travel in opposite directions down the wire at a speed determined by the density of the wire and its tension. If a sensor were placed near the wire that could measure its momentum, the sensor would display a voltage versus time that was a replica of the magnetic field versus position along the wire. If the sensor, instead, detected position, its output would be the time integral of the momentum, a replica of the integral of field versus position down the wire. This integral form is a particularly useful output because the angular deflection of an electron beam is proportional to this same integral. The wire arrangement has, in a simple analog fashion, performed the integral that is

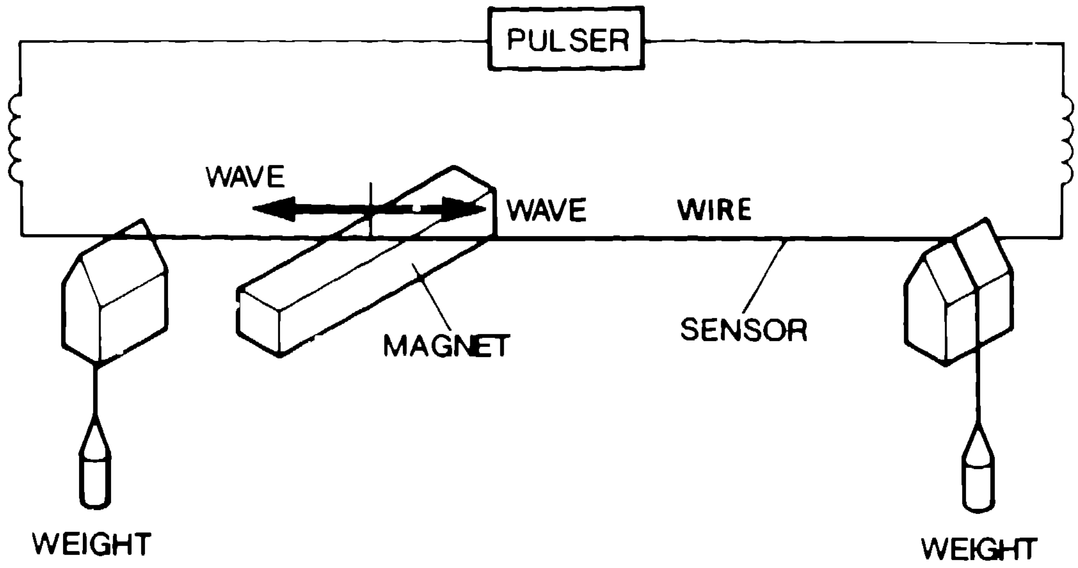

Fig. 5. Technique used to measure strength of single magnet.

conventionally evaluated from direct field measurements with considerably more difficulty, taking much more time.

To carry this technique a step further, we can modify the source of current to produce a step function instead of a delta function. The signal now developed by the position sensor is the *second* integral of the field strength versus position down the wire. Now, the transverse displacement of an electron beam is proportional to this second integral; thus, the use of a current step is particularly useful to display transverse displacement errors.

Other useful extensions of the wire technique can be imagined. For example, if a short current pulse of just the right length were used, a wire deflection would be produced that is caused by the field integated over exactly one wavelength of the wiggler. Because this integral should ideally be zero, very small deviations from perfection can easily be detected.

In a second example, because the sensor produces an electronic replica of the electron's path, its signal can be easily manipulated electronically to reveal, for example, the length of the electron's path and, thus, any accumulation of phase error as a function of position.

IV. CHARACTERIZATION OF SINGLE MAGNETS

Following procedures shown in Fig. 5, a 4-mil-diam copper wire was placed under tension with a 50-g weight and suspended over two bridges placed 0.5 m apart. A single magnet was placed near the wire at a distance of 0.44 cm, equal to the normal magnet-electron beam separation of a wiggler that we often use. A short 10-A current pulse was passed through the wire. The wire's deflection was determined by measuring its time-varying obstruction of a light beam. The light beam was generated and detected by a single, compact, convenient, commercially available electronic component (Slotted Optical Limit Switch #CMT8, manufactured by General Instruments, Optoelectronics Division, Palo Alto, California 94304).

When the magnet was oriented upright (transverse field) and the current pulse was short, the sensor's output, shown in Fig. 6, was proportional to the angular deflection of an electron beam. When the current pulse was changed to a step, the sensor's output, shown in Fig. 7, was proportional to the actual displacement of the electron beam. The angular deflection of an electron beam caused by such a magnet is about 1 mrad, illustrating the sensitivity of this method.

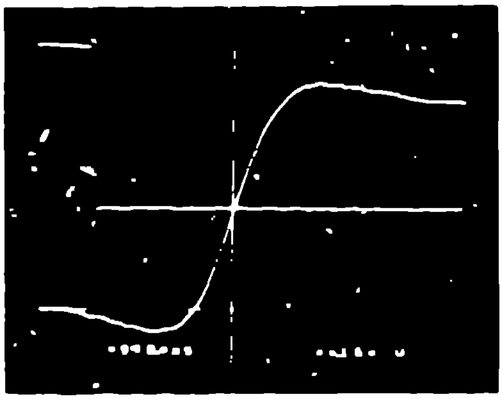

Fig. 6. Measurement with single upright magnet. Short current pulse.

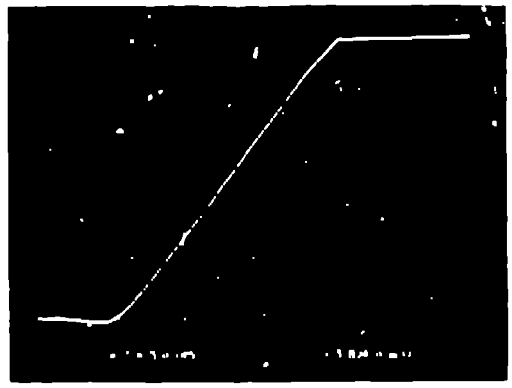

Fig. 7. Measurement with single upright magnet. Step pulse. The sharp kink in the upper right-hand corner is caused by a nonlinearity in the amplifier.

When the magnet was oriented sidewise, the corresponding pulse and step responses were as shown in Figs. 8 and 9. The real spatial deflection of an electron beam caused by such a magnet is about 10 μm.

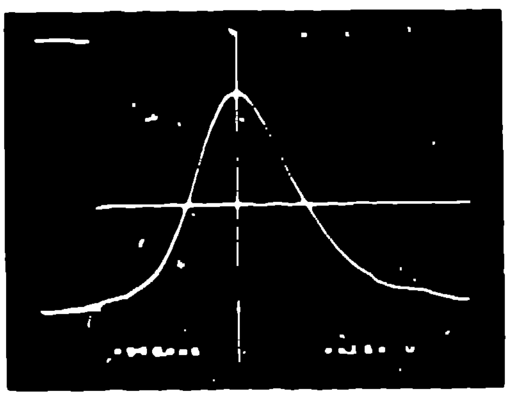

Fig. 8. Measurement with single sidewise magnet. Short pulse.

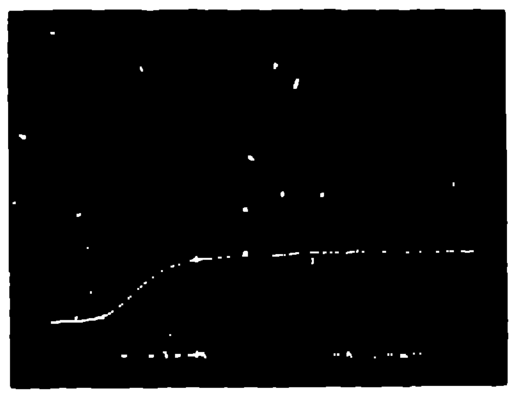

Fig. 9. Measurement with single sidewise magnet. Step pulse.

A magnet's essential properties can be determined by performing and cataloging these pulse and step responses. Advantages in precision can be gained, however, by employing a null technique and recording differences. If a standard magnet is placed on one side of the wire and a test magnet with reversed magnetization is placed opposite it, their two fields will cancel at the wire's position so that only the difference of their field integrals is recorded. By using this null technique, we were able to measure differences between magnets of less than 0.1%. Real magnets always produce error fields that are parallel to the magnet's long dimension; such field errors cannot be ignored. An extra sensor can be added to the configuration of Fig. 5 to measure the fields of this orientation. As discussed above, partial cancellation of these fields can be accomplished by a selection process when the frames are assembled.

V. CHARACTERIZATION OF FRAMES

Advantage can be taken of another symmetry property of the arrangement shown in Fig. 5. The test and standard magnets can be replaced by one of the half-wavelength frames described above. If a second frame is placed symmetrically on the other side of the sensor, the sensor will detect two waves, one from the standard frame and the other from the test frame. If the magnetization directions are correctly chosen and the separations from the sensor are truly equal, one wave will cancel the other, and only the difference between the frames will be detected. The focusing magnets on the test frame can then be adjusted to null the difference signal. This technique has been tested and also provides a sensitivity of 0 1% or better.

VI. CHARACTERIZATION OF A WIGGLER

A long wire was passed through a conventional 1-m wiggler, and short and step pulses were passed through it as described above. Figure 10 shows the results for a short pulse and Fig. 11 for a step. This wiggler had been in use and its errors were determined not to seriously affect the wiggler's performance. Errors, however, are clearly evident, particularly in Fig. 11. A wiggler is considered to be free of gross errors if its trajectory wanders transversely less than the amplitude of its wiggles.

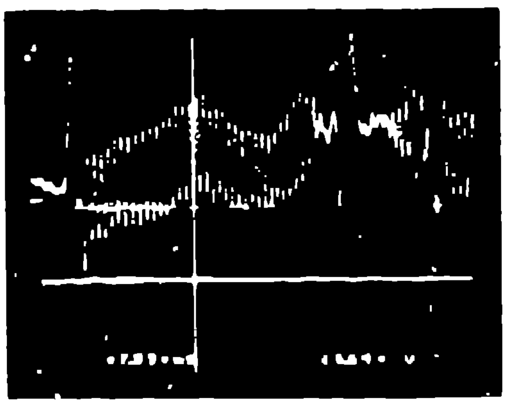

Fig 10. Measurement with wiggler. Short pulse

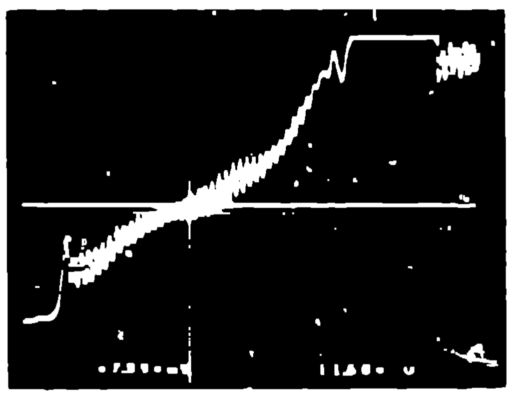

Fig. 11. Measurement with wiggler. Step pulse.

This is not quite true of Fig. 11, which shows a large angular error at the left end (entrance) of the wiggler (corrected in use by steering at this end) and smaller errors internal to the wiggler that were not accommodated in any way. If this wiggler had convenient mechanical adjustments like those proposed above or if it had been fitted with closely spaced steering coils, we could have easily modified the fields until a flat measurement resulted. In this way the field errors could have been reduced by a factor of 1C or better.

VII. ON-LINE USE

Figure 12 shows an application of this technique to wigglers that are mounted in their final position ready to lase. In the normal fashion, a wire is threaded through the wiggler, supported by two bridges; its position is observed by several externally supplied light sources. When lasing is desired, the bridges are withdrawn so that the wire lies against the wall of the vacuum tube that penetrates the wiggler. The wake field introduced by the wire will be very small. When information is

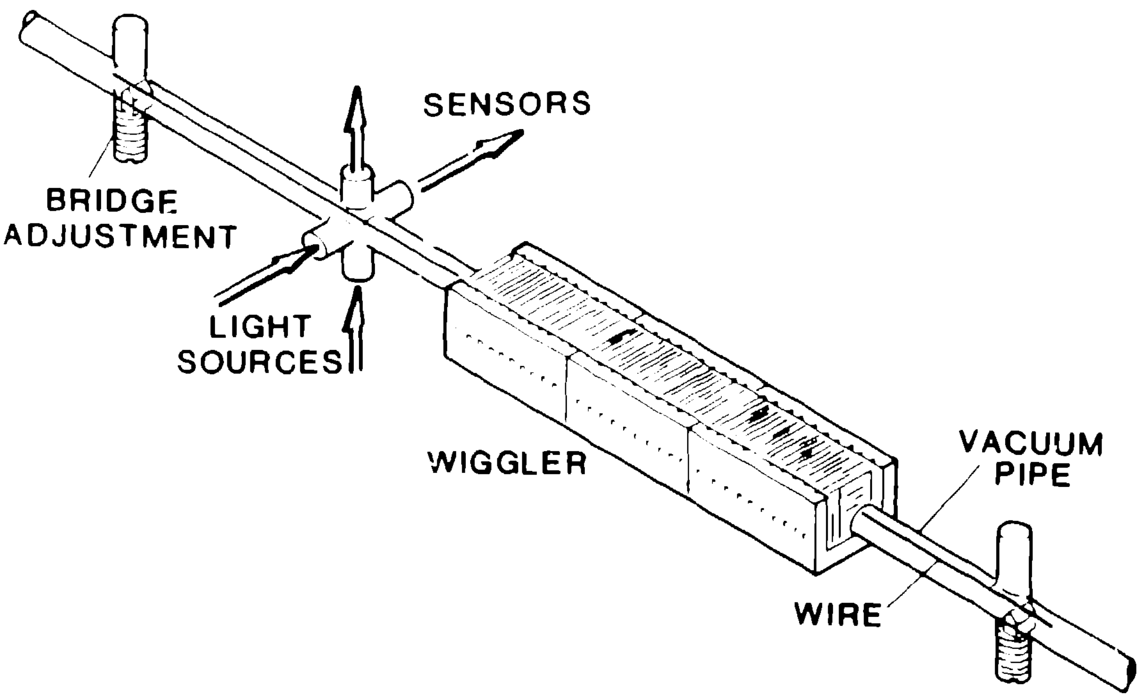

Fig. 12. Use in on-line application.

required about field uniformity, perhaps at the beginning of each day, the bridges are raised and the wire is moved into the center of the wiggler. A pulse is passed through the wire, and a signature like that of Fig. 11 is obtained. Once the errors are analyzed, corrective action can be taken by activating one or more steering coils. It should be fairly easy to assign this field correction process entirely to computer control. In this way, periodic correction of the field errors can be a simple, time-efficient process, and complete records can easily be maintained of any accumulation of errors owing, for example, to radiation damage.

VIII. REMAINING PROBLEMS

Four problems have come to our attention in preliminary examinations of this technique:

Magnet Stability

The use of focusing magnets in the manner shown in Fig. 2 subjects these and the adjacent magnets to unusually large demagnetizing forces. Some, but not all, varieties of magnets can sustain the stress.

Wire Sag

The measurements described above for complete wigglers were carried out with the wiggler's axis oriented vertically. If the axis had been horizontal in the usual fashion, the wire would have sagged. For a 1-m wiggler, the amount of sag would have been insignificant, but because the sag varies as the square of the wire's length, it becomes prohibitively large (0.1 to 1 cm) for wigglers 10 m or so long. We have solved the sag problem by levitating the wire with a combination of a constant horizontal field produced by the steering coils and a low but constant current through the wire. The magnitudes of the currents are modest as are the requirements on the precision of their settings.

Betatron Motion

An electron beam senses the magnetic field along its entire trajectory, wiggles and all, and is, therefore, sensitive to the gradients of the field. The gradients, among other effects, generate focusing forces and the betatron motion. When using the dc floating-wire technique, one could choose the correct experimental parameters so that the wire's deflection would simulate the electron beam in detail and demonstrate the focusing and betatron motions caused by the wiggler. Such a demonstration is not as simple with our pulsed technique because of the complexities introduced by the existence on the wire of two oppositely moving waves. Gradients can still be investigated by measuring field integrals at closely spaced transverse locations.

Nonideal Wire Properties

The wire is not perfect in its dynamical behavior. As a pulse progresses along the wire, it can change its shape for several reasons, for example by dispersion, attenuation, reflection at irregularities, or by rotation of polarization at irregularities. Dispersion is the most noticeable effect, while path lengths of tens of meters must be used to see significant attenuation. Reflection and polarization rotation have not been observed.

Dispersion is caused by the stiffness of the wire. It causes short wavelength components of the wire's deflection to travel with higher velocities than longer wavelengths. Dispersion can be minimized by choosing a thin wire of the best material (low stiffness/high strength) and by operating it at a tension near its breaking point. Dispersion is a problem for wigglers 10 m long, but not for shorter ones.

Both dispersion and attenuation are predictable events; therefore, a computer code could presumably be written to process the raw data produced by a sensor and correct for these effects. In any event, the main effect of dispersion is to distort the high-frequency parts of the sensor's signal, i.e., the details of the wiggle motion. The part we are most interested in, the wandering, is contained in the low-frequency, undistorted parts. If a short (but not delta function) current pulse is used as was discussed above, the wiggle motion of the wire can be almost completely suppressed so that only the wander motion is displayed.

IX. CONCLUSIONS

A new technique has been demonstrated for measuring magnetic fields. It has three distinct applications to wigglers: the measurement of individual magnets, the measurement of completed wigglers, and the on-line measurement of wigglers that are installed in their final lasing positions. The technique naturally produces electrical signals that are proportional to the first and second integrals of the magnetic field versus position down the wire. These integrals are direct analogs of the most important properties of the electron beam, its angular and spatial deflection down the wiggler. The measuring techniques have special symmetry properties that make null measurements easy to perform. The elastic properties of wires place limits on the length of the wiggler that can successfully be used with these techniques. Ways around these limits are now being investigated.

ACKNOWLEDGMENTS

Brian Newnam suggested and encouraged the work reported in this paper. Noel Okay and Richard Martinez helped with fabrication of the test equipment.

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